

SABRE ENGINE: Single Stage to Orbit Rocket Engine

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ABSTRACT: Present study focuses on the special kind of powerplant, which can take an aircraft from surface of earth to the orbit of earth. Commonly known as SABRE Engine. It's also known as Single Stage to Orbit engine. It's basically a combination of both air breathing engine and rocket engine. As to send one or more personals into space utilize whole of one rocket and tons of propellant which leads to an expensive mission whereas use of sabre not only reduce the cost (because in atmosphere it is used as air breathing engine which suck the oxygen directly from atmosphere) also increase the easiness.

KEYWORDS: Rocket Engine, Single stage to orbit, Sabre, Liquid air cycle engine, Brayton cycle, Skylon.

I. INTRODUCTION

Several attempts have made by aerospace engineers to design Single stage to orbit vehicle (SSTO) propulsion system but all in vain due to large weight of stocked oxidizer, essential for traditional rocket engine [1] have done several attempts. One way, which have incredible potential as the solution for this difficulty, is use of environmental oxygen as oxidizer in combustion process like air breathing jet engines. This weight minimization allows the evolution from single-use multi-stage (SUMS) launch vehicles to multi-use single stage (MUSS) launch vehicles [2]. SABRE(Synergistic Air-Breathing Rocket Engine) is the first engine to accomplish this goal by effectively functioning in two rocket modes: primarily in air-breathing mode and later on in traditional rocket mode, to power aerospace vehicle in SSTO mode. Ultimately, to permit cost effective, reliable, responsive space exploration with increase payload [3] also to allow aerospace vehicle to cruise at low hypersonic speed (around Mach5.5) within the earth's atmosphere.

In primary mode or air breathing mode, SABRE engine Sucks atmospheric oxygen as oxidizer to burn with stocked liquid hydrogen. After achieving Mach 5.5 and 28.5 km altitude engine engaged into the secondary rocket mode and use on bard stocked oxygen like conventional rocket engines. In both modes of engine, the thrust is produced via the rocket combustion chamber and nozzles, made possible by synthesis of rudiments of gas turbine and rocket technology. The paper deals with a study on SABRE engine and its dominance over conventional propulsion system. The paper is sectioned as following: Second section deals with System components, third one depicts performance of engine, fourth section offers a coversetion on history and present performance and finally fourth concluded the study.

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II. HISTORY & CURRENT STATUS

The pre-cooler concept of SABRE engine derived from the concept introduced by Robert P. Carmichael in 1955 [4], followed by the LACE concept reconnoitered by General Dynamics in the 1960 [5].

As a part of the HOTOL project the Rolls Royce RB545 engine was developed with a more efficient cycle compare to LACE. In 1989, after funding for HOTOL project stopped, Bond and several other founded Reaction Engines Limited to continue the research on HOTOL concept. The pre-cooler of RB545 had some disputes with embrittlement, excess LH2 consumption, patents and some Official Secrets Act, so RE Developed SABRE [6].

In November of 2012, hardware experimentation of the heat exchanger technology essential to SABRE had been successfully completed, demonstrated viability of the technology [7]. The SABRE engine bank on on a heat exchanger adequate of cooling of incoming air upto $-150\text{ }^{\circ}\text{C}$ ($-238\text{ }^{\circ}\text{F}$), to offer LOX for mixing with hydrogen to provide jet thrust during atmospheric flight before terminating to the rocket mode. The experiments confirmed the performance of heat exchanger to suck sufficient and suitable oxygen from the earth's atmosphere to support the high-performance operation even in low altitude [5] [6]. In 2015, the SABRE passed all the feasibility tests accomplished by the Research Laboratories U.S. Air Force.

III. SYSTEM COMPONENTS

Like RB545, a Rollce Royce (RR)engine concept for Horizontal Take-off and Landing (HOTOL) [8], SABRE is a hybrid of air breathing engine and rocket engine, evolved from Liquid-Air Cycle Engines (LACE) and works on combined cycle of brayton cycle and having a single rocket combustion chamber with associated pumps, pre-burner and nozzle, exploited in both modes to use environmental air for low altitude and speed and afterwards uses liquid oxygen (LO_2) for higher altitudes to work as a rocket engine[2], .

A simple translating axisymmetric shock cone inlet, at front of the engine, slowdowns the sucked environmental air to subsonic speeds by means of two shock reflections. Some part of the sucked hot air passes radically through a precooler into the central core, with leftover passes through a ringlet of bypass ramjets. Central core of SEBRE after the precooler implements a Turbo-compressor (TC)operates on the same helium (He) loop and Brayton cycle that compresses the air and leads it into the combustion chamber. For rocket mode oxygen is used as oxidizer and fed to the combustion chamber [9].

The study of system components is classified as follows: 1. Pre-cooler 2. Compressor 3. Helium loop 4. Bypass thruster 5. Engines & 6. Nozzle. Figure 1 illustrates schematic diagram of SABRE engine.

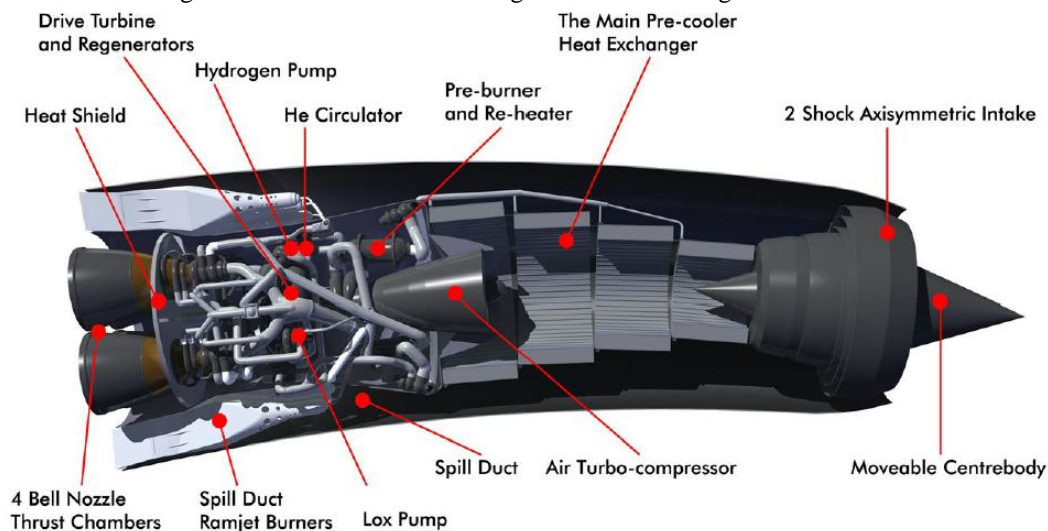


Fig. 1. SABRE Engine Schematic

1. PRECOOLER:

Due to compression effects sucked environmental air at supersonic/ hypersonic speed becomes very hot. Conventionally, in jet engines this high temperature is dealt using heavy Nickel (Ni) or Copper (Cu) based material, by reducing the pressure ratio and by strangling back the engine at higher airspeed to elude melting. But in SSTO vehicles, heavy materials are useless due to weight problems and throttling is not done to get maximum thrust out of it for orbital insertion and to escape earth's gravity earliest to minimise gravity losses.

Sabre design is emerged from Liquid-Air Cycle Engine (LAC) concept [1]. LACE utilizes the cooling capability of cryogenic liquid hydrogen(LH₂) to liquefy incoming environmental air before pumping, but regrettably liquefied air needs high fuel flow. The stated problem is solved in SABRE by cooling down the air to the vapour boundary (from 1000°C to -150 °C in 0.01 sec), avoiding liquefaction eliminating blocking by freezing of liquid vapour as well as cooling requirement and LH₂ flow, using heat exchanger in pre-cooler and endorse the need of a relatively traditional turbo compressor. For cooling in pre-cooler is achieved by He itself cooled by liquid hydrogen. For prevention of ice formation, a methanol-injecting 3D-printed dicer is implemented to prevent ice formation [9].

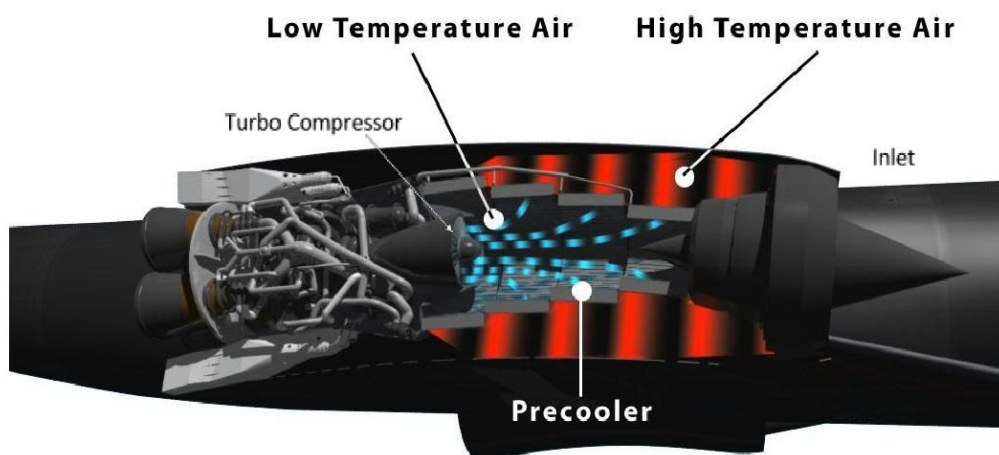


Fig. 2. SABRE engine schematic

As illustrated in figure 2, inlet slows down the sucked air and guides to the outer fringes, which flows inward through the pre-cooler and lead to compressor. Figure 3 exhibits a comprehensive depiction of pre-cooler used by Reaction Engines Ltd. (RE) in SEBRE engine. As the hot sucked air travel axially across it, some of flow is caught radially inside it and crosses a number of small chained pipes filled with HE flow, results in conversion from hot air to cold air, design guarantees cool down of air upto a desired temperature preventing liquefaction [2].

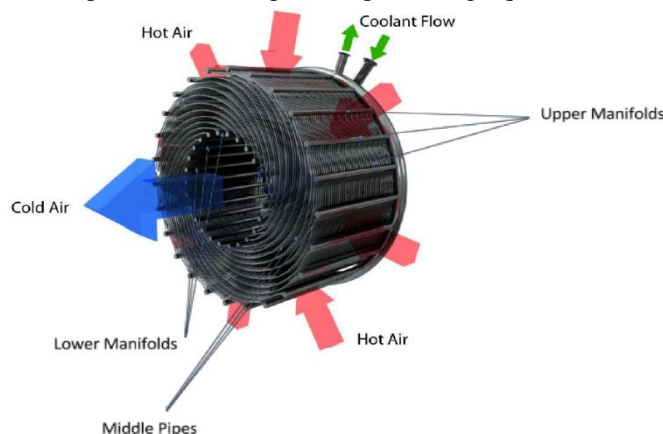


Fig. 3. Pre-cooler design

2. COMPRESSOR:

In the air breathing mode of engine air cooled by the pre-cooler passes into redesigned TC similar to conventional jet engines' turbo compressor but operating abnormally at high pressure ratio, facilitated by the low temperature of the precooled air. Precooled air compressed by the compressor at high pressure of 140 atmospheres leads to the rocket combustion chamber to combust with stocked liquid hydrogen (LH2). Instead of powered by combustion gases like jet engine, TC is powered by a gas turbine operating on waste heat collected by a HE loop. Figure 4 illustrates turbomachinery of SABRE engine,

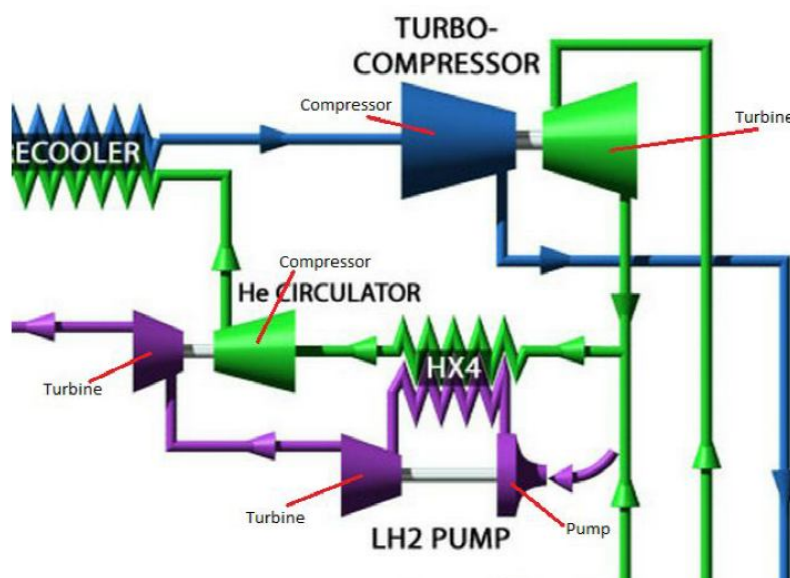


Fig. 4. Turbomachinery of SABRE engine

3. HELIUM LOOP:

The hot HE from the pre-cooler is reprocessed by cooling it in a heat exchanger with the LH2, heat absorbed by HE from incoming air is utilised to power various parts of engine developing a self-starting Brayton cycle based engine [9].

4. BYPASS THRUSTER:

Avoiding liquefaction by using heat exchanger in pre-cooler, generating less entropy results in improved engine efficiency and boil off of less amount of liquid hydrogen, compare to amount required for artlessly cooling the air with that can be used to burn in the engine core [6]. The excess is eliminated by using a series of spill duct ramjet burners, arranged in a ring around the central core, fed with air that bypasses the pre-cooler, is framed to minimise the undesirable effects of drag due to air that passes into the intakes but not fed into the main rocket engine, rather than generating appreciable thrust [1]. At low speed the volume of air that compressor supply to combustion chamber is at peak, requiring to accelerate the bypassed air to retain efficiency at these low speeds. This differentiate the system from a conventional turbo-ramjet system where exhaust of turbine-cycle is used to increase air-flow for the ramjet to become adequate efficient to substitute the role of elementary propulsion system [10].

5. ENGINES:

Static thrust potential of SEBRE engine, makes aerospace vehicle capable to take off in air breathing mode like conventional jet engines. With increasing altitude escalation pressure decreases and suck more and more air into the compressor as the effectiveness of ram compression decreases with pressure drop [11]. As the aerospace vehicle climb, outside air pressure varies with altitude change and more and plenty more amount of air is sucked into the compressor

to maintain the performance of the ram compression and makes jets capable to function efficiently at much higher altitude than an aerospace vehicle with conventional technique.

Air-breathing system becomes incompetent and powered down beyond Mach 5.5, [11] and substituted by on board stocked oxygen as fuel in rocket mode, [12] allows the engine to operate at much higher velocity needed to accelerate the aerospace vehicle to much higher orbital velocities (about Mach 25) [3].

6. NOZZLE:

SABRE engine operates a single array of nozzle, rather using multi stage concept like traditional rockets. RE performed several experiments on an expansion-deflection nozzle, named STERN, to swamp the non-dynamic exhaust expansion problem, [13] and found the 80% bell nozzle design as optimal solution, as shown in figure 5. [14]

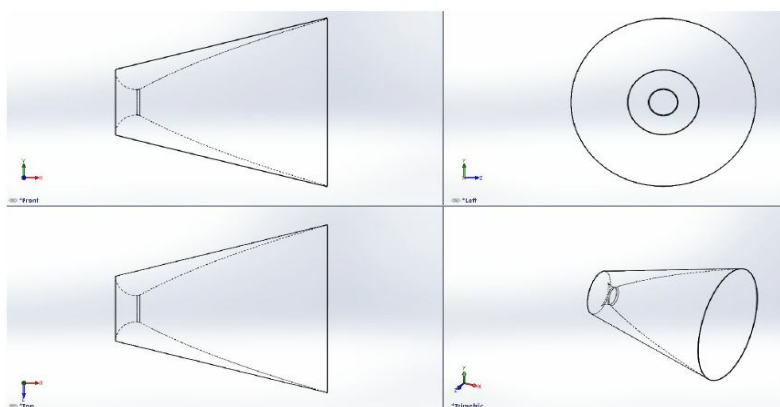


Fig. 5. CAD design of 80% bell Nozzle

IV. WORKING

The SABRE engine is principally a closed cycle rocket engine with an added pre-cooler, followed by turbo-compressor to provide a high pressure air supply, like in air breathing jets engine to the combustion chamber, permits it to operate from rest on to Mach 5.5 with air-breathing mode during climb [6]. With density fall due to altitude ascent the engine ultimately shifts into pure rocket mode propelling the aerospace vehicle to orbital velocity (above Mach 25).

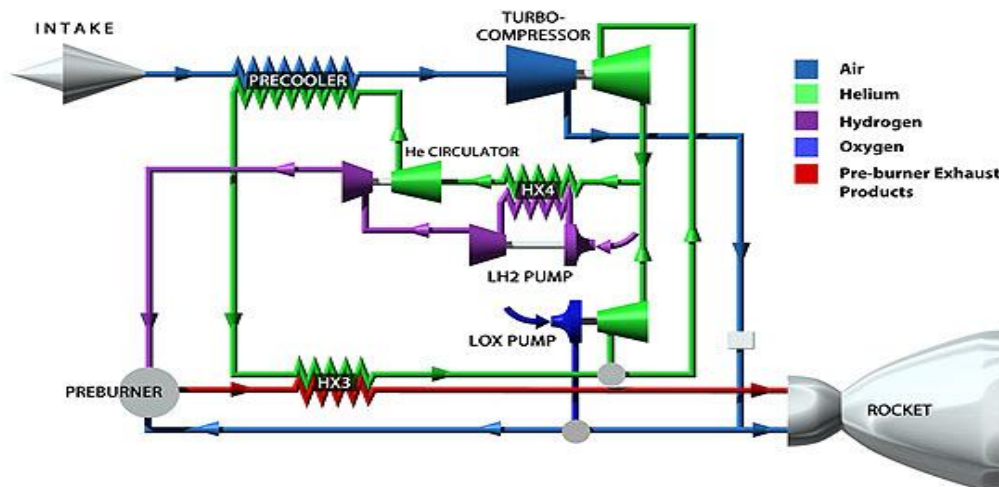


Fig. 6 Working cycle of SABRE engine

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The figure6 depicts the complete SABRE cycle. The atmospheric air, sucked by the intake (blue), is leading to Pre-cooler and then into the compressor. The cooling of hot sucked air is accomplished with (HE) (green), cooled by HX4 via the LH2 fuel (purple). After parting from the Pre-cooler the HE gets auxiliary heated in HX3 by the products of the Pre-burner to deliver it sufficient energy to provide the turbine and then LH2 pump [14].

In rocket mode, HX3 offers all the energy to operate the LH2 pump and the LOX pump. Recycling the heat in such a way enhances engine efficiency. In rocket mode on board stoked LOX used as oxidizer [1].

Exemplar based inpainting technique is used for inpainting of text regions, which takes structure synthesis and texture synthesis together. The inpainting is done in such a manner, that it fills the damaged region or holes in an image, with surrounding colour and texture. The algorithm based on patch based filling procedure. First find target region using mask image and then find boundary of target region. For all the boundary points it defined patch and find the priority of these patches. It starts filling the target region from the highest priority patch by finding the best match patch. This procedure repeated until entire target region is inpainted.

The algorithm automatically generates mask image without user interaction that contains only text regions to be inpainted.

V. PERFORMANCE

RE Engineers designed Sabre engine with Thrust to weight ratio (TWR) of 14, a higher value than jet engines with TWR of 5 and 2 for scramjet engines, by virtue of the combination of number of properties of SABRE engine – denser and cooled air require less compression, and low air temperature allows the use of lighter alloys in engine [3].

Specific impulse for SEBRE engine achieves as high as 3500 seconds within earth's atmosphere, is a great performance compared to other rocket propulsion system which is succeed to attend around 450 seconds only and for nuclear thermal rockets about 900 seconds [15].

The grouping of above discussed properties that is high fuel efficiency with lightweight engine allows an aerospace vehicle for SSTO approach with air breathing mode up-to altitude of 17.709 miles and Mach 5.14. As well as to increase payload [16] than just than any other existing non-nuclear launch vehicle makes it to breakthrough once again in propulsion system after invention of jet engines.

The precooler concept, like introduced in RB545 engine, integrates mass and complexity to the system and most threatening and complex design part. After performing several experiments, SABERE team of RE succeeded invent a device with heat transfer of almost 1 GW/m^3 , believed as world record [8].

The losses comes into account due to auxiliary weight of systems which has stopped working during rocket mode or close cycle mode and the extra weight of Skylon's wings negate the earning in overall efficiency and desired flight plan [11]. State of art launch vehicles devote about one minute for almost vertical climb at relatively low speed, which is inefficient but optimal for traditional launch vehicles. Whereas SABRE engine allows an launching vehicle to climb much slower and shallower in air breathing mode with supporting wings but with far lower fuel consumption, results in saving on propellant weight and increment in payload mass [14].

The conventional Ramjets and Scramjets must devote significant time in earth's atmosphere to gain enough speed to reach orbital velocity devoting concerns with exceptionally high drag resulting to intense heating and ensuing weight and complexity of required thermal shield [15]. An aerospace vehicle with hybrid jet, like Skylon with SABRE engine, gains low hypersonic speed in Earth's atmosphere before engaging in rocket mode for whist climbing to achieve higher hypersonic accelerating speed. Moreover, the potential of providing high thrust with speed from 0 to Mach 5.5 with outstanding thrust over the entire flight from ground to very high altitude but efficiently makes SEBRE engine as a dominant solution for launching vehicles over the up to date launching vehicles [17].

VI. CONCLUSION

Such kind of engine could become the future of aviation and space industry, which may ease many missions from earth's surface to space. Further modification in this engine may lead not only to orbit but also far away from that. Such Engine could make possible space tourism for people belongs to any community. This is a revolution for the upcoming era.

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